

To appear in *The Astronomical Journal*

Detection of Intergalactic He II Absorption at Redshift 3.5¹

Wei Zheng², Kuenley Chiu², Scott F. Anderson³, Donald P. Schneider⁴, Craig J. Hogan³,
Donald G. York⁵, Scott Burles⁶ and Jonathan V. Brinkmann⁷

ABSTRACT

The large number of quasars found in the Sloan Digital Sky Survey has allowed searches for elusive, clear lines of sight towards He II Ly α absorption, a sensitive probe of the intergalactic medium. The few known systems indicate that He II reionization occurs at $z > 3$. We report the detection of a He II Ly α absorption edge in a quasar spectrum at $z = 3.50$, the most distant such feature found to date. The candidate quasar was selected from a $z \sim 3$ sample in the SDSS spectroscopic quasar survey and confirmed as part of an *HST/STIS* SNAP survey. We discuss the general characteristics of the absorption feature, as well as the probability for discovery of additional such objects.

Subject headings: Dark matter — Intergalactic Medium — Quasars: Individual (SDSSJ2346-0016) — Surveys — Ultraviolet: General

1. INTRODUCTION

Much of the intergalactic hydrogen exists in a highly ionized state as evidenced by the lack of H I Gunn-Peterson troughs in the optical spectra of high-redshift quasars (Gunn

¹Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program GO 8582 and 9067.

²Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218

³Department of Astronomy, University of Washington, Seattle, WA 98195

⁴Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802

⁵Department of Astronomy, University of Chicago, Chicago, IL 60637

⁶Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139

⁷Apache Point Observatory, New Mexico State University, Sunspot, NM 88349

and Peterson 1965). The first presence of a Gunn-Peterson trough was detected in He II absorption, in a quasar at $z = 3.28$ (Jakobsen et al. 1994). Follow-up observations at a higher S/N level and spectral resolution (Hogan et al. 1997; Heap et al. 2000) found an average He II optical depth $\tau = 4.0 \pm 0.5$ at $z \sim 3$ and at least $\tau = 5$ at $z \sim 3.2$. He II absorption displays significant structure, consisting of unabsorbed void regions and deep absorption troughs (Reimers et al. 1997). When contrasted with the low He II opacity measured at $z \sim 2.5$ (Davidson et al. 1996; Kriss et al. 2001; Zheng et al. 2003) these findings indicate a sudden increase in optical depth. While the large opacity at $z \sim 3.2$ is conceivably related to a fluctuation in the number of local ionizing sources, it may instead (e.g., if confirmed in multiple additional independent sightlines) more generally signal an epoch in which intergalactic helium is not fully ionized. Recently, a similar pattern for intergalactic hydrogen has been observed in the $z > 6$ quasars. Becker et al. (2000) and Fan et al. (2002) report a H I optical depth of at least $\tau = 15$ at $z \sim 6.2$, signaling the late stages of reionization of the intergalactic medium (IGM). The recent *WMAP* results (Spergel et al. 2003) suggest that the IGM reionization may have started at $z \sim 17$, and there may have been a second stage of hydrogen reionization that took place at $z \sim 6$ (Cen 2003).

The reionization of intergalactic hydrogen and helium are cosmic milestones. As the early universe cooled and evolved, neutral hydrogen atoms in the IGM gradually became bathed in the ionizing ultraviolet background radiation produced by the first stars and quasars. With increasing UV background radiation, the IGM eventually became fully ionized. Atomic hydrogen and helium are affected by the same ionizing UV radiation in the distant universe – but because the He II Ly α transition is related to the number of ionizing photons at 4 Rydbergs (generally smaller than the number at 1 Rydberg), the the reionization of intergalactic helium is expected to occur later than hydrogen, approximately at $z \sim 3 - 5$ (Haardt and Madau 1996; Madau et al. 1999; Wyithe and Loeb 2003). Indirect evidence (Theuns et al. 2002) suggests that the final stage of He II reionization may take place at $z \sim 3.2 - 3.4$, but only a very small number of independent sightlines have thus far been identified that are suitable to probe He II even to $z \sim 3$. Moreover, each such sightline is potentially susceptible to systematic bias; these sightlines are, by selection, the most unobscured of all known quasar sightlines to high redshift. It is therefore important to find additional sightlines (to average over possible systematics in global conclusions), and also to extend He II studies to higher redshift. Higher redshift sightlines are, of course, potentially the most useful as each such object may provide a measure of He II absorption spanning the full redshift range likely to be most interest. Our knowledge of the intergalactic helium has been derived from only four lines of sight, and only two are between $3.0 < z < 3.3$. More such examples are needed to establish the statistics and evolution of intergalactic helium at redshift $z > 3$. The discovery of any bright, UV-unobstructed quasar in this redshift range

is therefore interesting.

We report here the detection of a He II absorption feature in the spectrum of quasar SDSS J234625.67-001600.4 (hereafter abbreviated as SDSSJ2346-0016), the highest redshift He II feature found to date. This new quasar sightline potentially will allow a measure of He II absorption from $z = 2.8$ to $z = 3.5$ in a single object, efficiently sampling the full redshift range commonly suggested for the epoch of helium reionization. We describe the method of selection, preliminary observations from *HST/STIS*, and the probability for further discovery of similar objects.

2. CANDIDATE SELECTION AND OBSERVATIONS

At redshift $z \gtrsim 2.8$ the He II Ly α feature becomes observable with *HST*. However, the observed UV flux of most high-redshift quasars is strongly suppressed by absorption from intergalactic H I along the line of sight. For objects at $z \sim 3$, attenuation by individual Ly α forest lines is moderate at restframe wavelengths shortward of ~ 600 Å, but Lyman-limit systems (LLSs) can remove significant – and frequently most – of the UV flux in high-redshift quasars (Møller and Jakobsen 1990). Not until recently have quasar catalogs provided sufficient numbers of bright, high-redshift candidates to begin to outweigh these difficulties. To date extensive searches have revealed only four such quasar sightlines with He II absorption features. Such a sample is too small to confidently understand the possible systematic uncertainties in the resulting cosmological inferences.

The Sloan Digital Sky Survey (SDSS; York et al. 2000) plans to image a quarter of the sky through five broadband filters (Fukugita et al. 1996) and to obtain spectra of approximately one million galaxies and 100,000 quasars. The survey employs a dedicated 2.5m telescope at Apache Point Observatory to obtain images (Gunn et al. 1998), and automated pipelines (Pier et al. 2003; Smith et al. 2002; Stoughton et al. 2002) process the data. Objects were selected based on their broadband SDSS colors (Hogg et al. 2001). Richards et al. (2002) describe the SDSS quasar selection algorithm. The spectrophotometric calibration includes scaling by wider aperture "smear" exposures to the photometry from the imaging data. Details regarding the spectroscopic system and analysis pipelines may be found in Stoughton et al. (2002) and Blanton et al. (2003). The Early Data Release (EDR) Quasar Catalog contains 3814 quasars, 3000 discovered by the SDSS (Schneider et al. 2002). The redshift-magnitude distribution of the 302 EDR quasars at $z > 2.5$ are shown in Figure 1.

The SDSS provides an excellent sample in which to search for quasar candidates with He II absorption features. We selected a sample of optically bright ($i < 18.5$) quasars at

redshift $z > 2.9$ for an *HST* snapshot survey to search for He II absorption edges in the UV. The snapshot program used the Space Telescope Imaging Spectrograph (STIS); only one out of the 24 candidates observed by the programs exhibited flux at the expected location of He II absorption.

The optical spectrum of SDSSJ2346-0016 ($i = 17.8$) was processed using the standard SDSS spectroscopic data reduction pipeline, and is shown in Figure 2. The redshift is measured using the peak of several emission lines: C IV $\lambda 1549$, O I $\lambda 1304$, C II $\lambda 1334$, Si IV+O IV $\lambda 1400$, and Ly α , and the averaged value is $z = 3.49 \pm 0.03$. The Ly α forest lines set in at 5476.2 Å, corresponding to $z = 3.5047$.

The ultraviolet *HST*/STIS spectroscopic snapshot of SDSSJ2346-0016 was performed on 2002 May 18. The data were obtained with the G140L grating and a $52'' \times 0.5''$ slit, covering the wavelength range of 1150 to 1700 Å. The spectral resolution was approximately 1 Å, and the exposure time was 600 seconds. The *HST* spectrum extraction was done manually, and processed using the standard STIS pipeline for wavelength and flux calibration. Figure 3 shows the spectrum binned by 9 pixels (~ 2.7 Å). It was fit with a power-law continuum, a Ly α emission line, and an absorption edge. The fitted absorption edge is at 1369 ± 2 Å, with a longward continuum level at $f_\lambda \sim 10^{-16}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$. No flux is detected at the wavelengths below 1360 Å. Between 1330 and 1360 Å, the average flux is $(0.05 \pm 0.8) \times 10^{-17}$ ergs s $^{-1}$ cm $^{-2}$ Å $^{-1}$, corresponding to an optical depth of $6_{-3}^{+\infty}$.

The match between the redshifts of H I Ly α and the He II Ly α features strongly suggests, at a 98% level, that the observed UV absorption edge is not merely coincidental. The 2% probability is based on the expected number of LLSs per redshift interval (Storrie-Lombardi et al. 1994). If this observed break is a LLS, the restframe cutoff wavelength is at 920 Å or longer, due to the combined effect of high-order Lyman-series lines. Such a system would be at $z \sim 0.49$, and a pair of Mg II lines may be expected around 4163.7/4174.4 Å. Between 4160 and 4180 Å there are three absorption lines in the SDSS spectrum: 4180.6 Å (EW ~ 2.4 Å), 4167.3 Å (EW ~ 1.5 Å) and 4161.9 Å (EW ~ 4.4 Å). If any of them is Mg II 2803 Å, a counterpart feature is expected approximately at the wavelength 10.5 Å shortward. No such lines are identified within 2 Å at the expected wavelength and within 30% of the expected intensity (50%).

3. IMPLICATIONS

The study of He II absorption in this new unobscured quasar sightline (and others extending to similarly high redshifts) will allow significant progress in IGM studies. For

example, if helium in the IGM is not fully ionized at $z = 3.50$, the high He II opacity would result in a damping profile, which may be detected even at low spectral resolution (Miralda-Escudé et al. 1998). This profile is characterized by a redward wavelength shift of a trough from the expected position of He II Ly α emission, on the order of 2-10 Å. The limited signal-to-noise level of our detection spectrum is insufficient to accurately measure such a feature; future observations with STIS or COS (Cosmic Origins Spectrograph) with significantly longer exposures may establish conclusive evidence. The diagnosis of such a feature may be complicated by the proximity effect (Madau and Rees 2001), and residual infall of matter into the deep potential well of the quasar host galaxy may also give rise to such absorption feature (Barkana and Loeb 2002). However, previous observations of He II absorption in other $z > 3$ quasars suggest that these effect may not be always present, as high-opacity clouds near the quasar may block the ionizing radiation from the quasar itself (Heap et al. 2000).

Should future observations of this object reveal the proximity effect, the data are useful to estimate the intensity of the metagalactic UV background radiation (Zheng et al. 2003; Miralda-Escudé et al. 1998) and the baryon density of the IGM (Hogan et al. 1997; Anderson et al. 1999). It is known that He II absorption at $z > 3$ is represented by high opacity of $\tau > 3$. The wavelength baseline between 1050 and 1370 Å in a *HST* spectrum will be the longest to reveal the ionization history of intergalactic helium.

This detection strengthens our confidence in future discoveries of similar features at higher redshifts. Model simulations of the IGM (Møller and Jakobsen 1990) suggest a success rate of approximately 7% in finding a $z > 3$ quasar whose flux at 300 Å (restframe) may be detected. This appears to be consistent with our detection rate of 4% (one in 24 objects) and that of a similar program (*HST* GO 8287, one detection in 26 objects). While the lines of sight towards objects at even higher redshifts will encounter more intervening LLSs, these additional systems will not affect the He II detection in a significant manner – they set in at long wavelengths ($\gtrsim 4100$ Å), and their optical depths recover quickly with $\tau \propto \lambda^3$. Therefore, the effect on He II detection at $z > 3.5$ is determined mainly by the LLSs at $z < 3.5$. The large number of SDSS quasars should provide several hundreds of quasars at $z > 3.5$ that are sufficiently bright for future study. The cases confirmed to be unobscured will be studied with *HST*'s STIS and/or Cosmic Origins Spectrograph (COS) with significantly higher sensitivity.

The large span in IGM redshift accessible to He II studies in each such suitable high redshift quasar will provide critical information on the reionization history of the IGM. The anticipated large sample size will allow assessment of, and averaging over, potential systematic biases that may be present in the current critically small sample, as well as the

cosmological inferences obtained therefrom.

Funding for the creation and distribution of the SDSS archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the U.S. Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS Web site is <http://www.sdss.org/>.

The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are The University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, Princeton University, the United States Naval Observatory, and the University of Washington.

Support for this research was provided by NASA through grants 8582 and 9067 from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

REFERENCES

Anderson, S. F., Hogan, C. J., Williams, B. F., Carswell, R. F. 1999, AJ, 117, 56

Barkana, R., and Loeb, A. 2002, ApJ, 578, 1

Becker, R. H., et al. 2001, AJ, 122, 2850

Blanton, M. R., Lin, H., Lupton, R. H., Maley, F. M., Young, N., Zehavi, I., and Loveday, J. 2003, AJ, 125, 2276

Cen, R. 2003, ApJ, 591, 12

Davidsen, A. F., Kriss, G. A., and Zheng, W. 1996, Nature 380, 47

Fan, X., et al. 2002, AJ, 123, 1247

Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., and Schneider, D. P. 1996, AJ, 111, 1748

Gunn, J., and Peterson, B. 1965, ApJ, 142, 1633

Gunn, J. E., et al. 1998, AJ, 116, 3040

Haardt, F., and Madau, P. 1996, ApJ, 461, 20

Heap, S. R., et al. 2000, ApJ, 534, 69

Hogan, C. J., Anderson, S. F., and Rutgers, M. H. 1997, AJ, 113, 1495

Hogg, D. W., Finkbeiner, D. P., Schlegel, D. J., and Gunn, J. E. 2001, AJ, 122, 2129

Jakobsen, P., et al. 1994, Nature 370, 35

Kriss, G. A., et al. 2001, Science, 293, 1112

Madau, P., Haardt, F., and Rees, M. J. 1999, ApJ, 514, 648

Madau, P., and Rees, M. J. 2000, ApJ, 542, 69

Miralda-Escudé, J. 1998, ApJ, 501, 15

Møller, P., and Jakobsen, P. 1990, A&A, 228, 299

Pier, J. R., Munn, J. A., Hindsley, R. B., Hennessy, G. S., Kent, S. M., Lupton, R. H., and Ivezić, Z. 2003, AJ, 125, 1559

Reimers, D., Köhler, S., Wisotzki, L., Groote, D., Rodriguez-Pascual, P., and Wamsteker, W. 1997, *A&A*, 327, 890

Richards, G. T. et al. 2002, *AJ*, 123, 2945

Schneider, D. P., et al., 2002, *AJ*, 123, 567

_____ 2003, *AJ*, in press, (astro-ph/0308443)

Smith, J. A., et al. 2002, *AJ*, 123, 2121

Spergel, D. N., et al. 2003, *ApJS*, 148, 175

Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M. J., and Hazard, C. 1994, *ApJ*, 427, L13

Stoughton, C. et al. 2002, *AJ*, 123, 485

Theuns, T., Bernardi, M., Prieman, J., Hewett, P., Schaye, J., Sheth, R. K., and Subbarao, M. 2002, *ApJ*, 574, L111

Wyithe, J. S. B., and Loeb, A. 2003, *ApJ*, 586, 693

York, D. G., et al. 2000, *AJ*, 120, 1579

Zheng, W., et al. 2003, *ApJ*, submitted

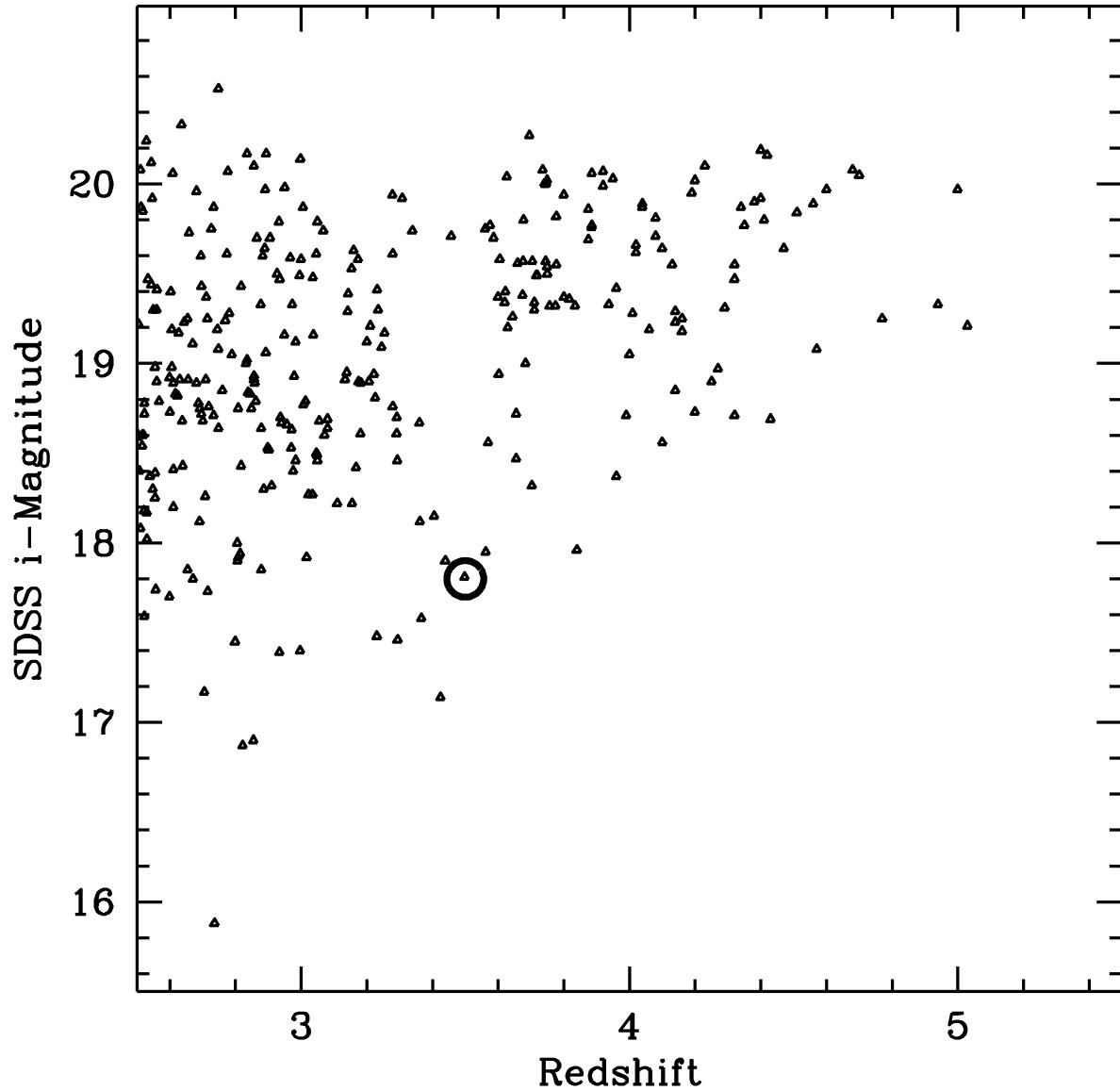


Fig. 1.— 302 quasars at $z > 2.5$ found in the SDSS EDR (Schneider et al. 2002). The circle marks the position for the newly discovered quasar SDSSJ2346-0016.

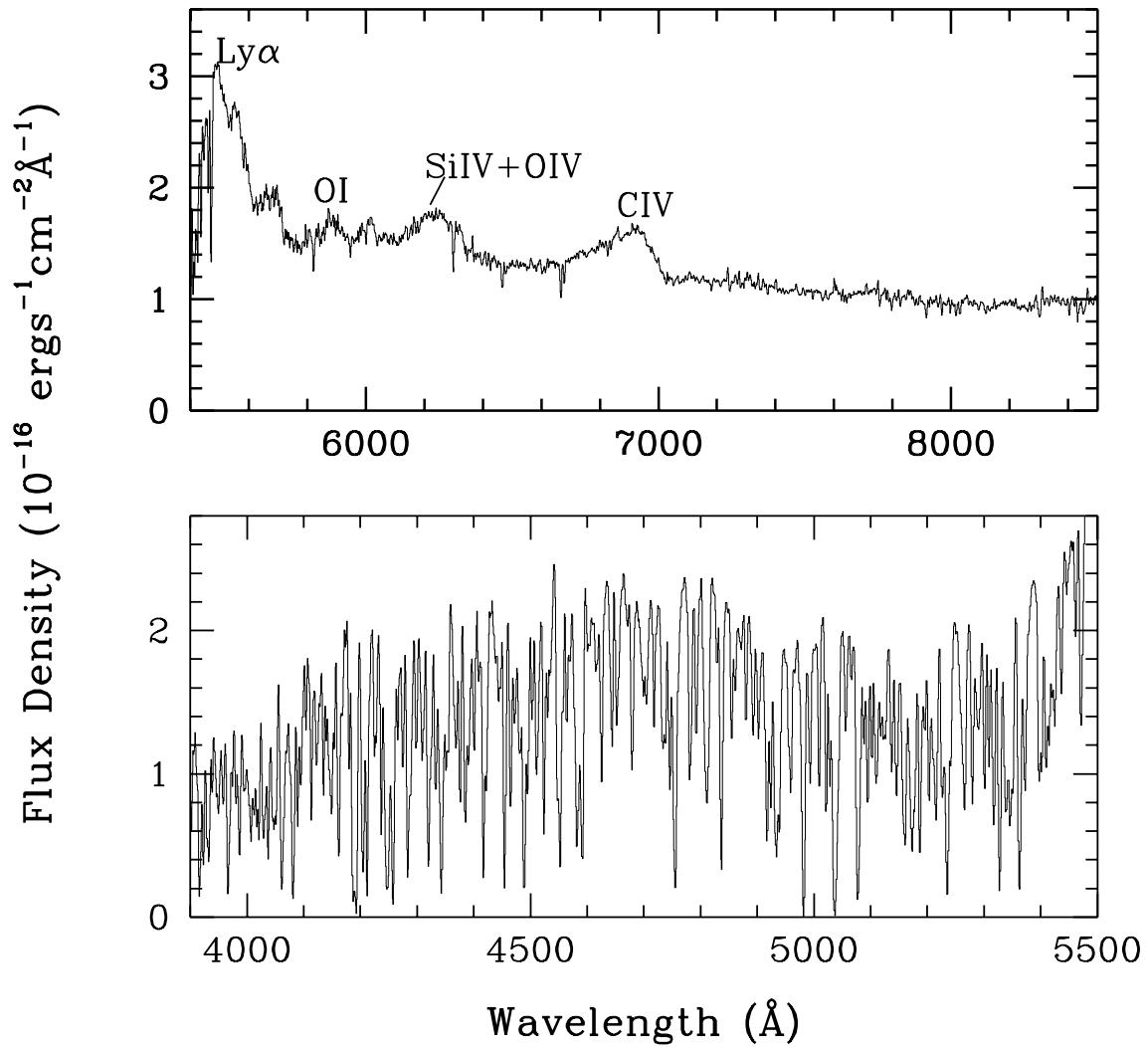


Fig. 2.— Optical spectrum of SDSSJ2346-0016. The spectral resolution is approximately 1900. The top panel displays the spectral region longward of 5400 Å, and the bottom panel for the Ly α forest region. Major emission lines are indicated in the figure.

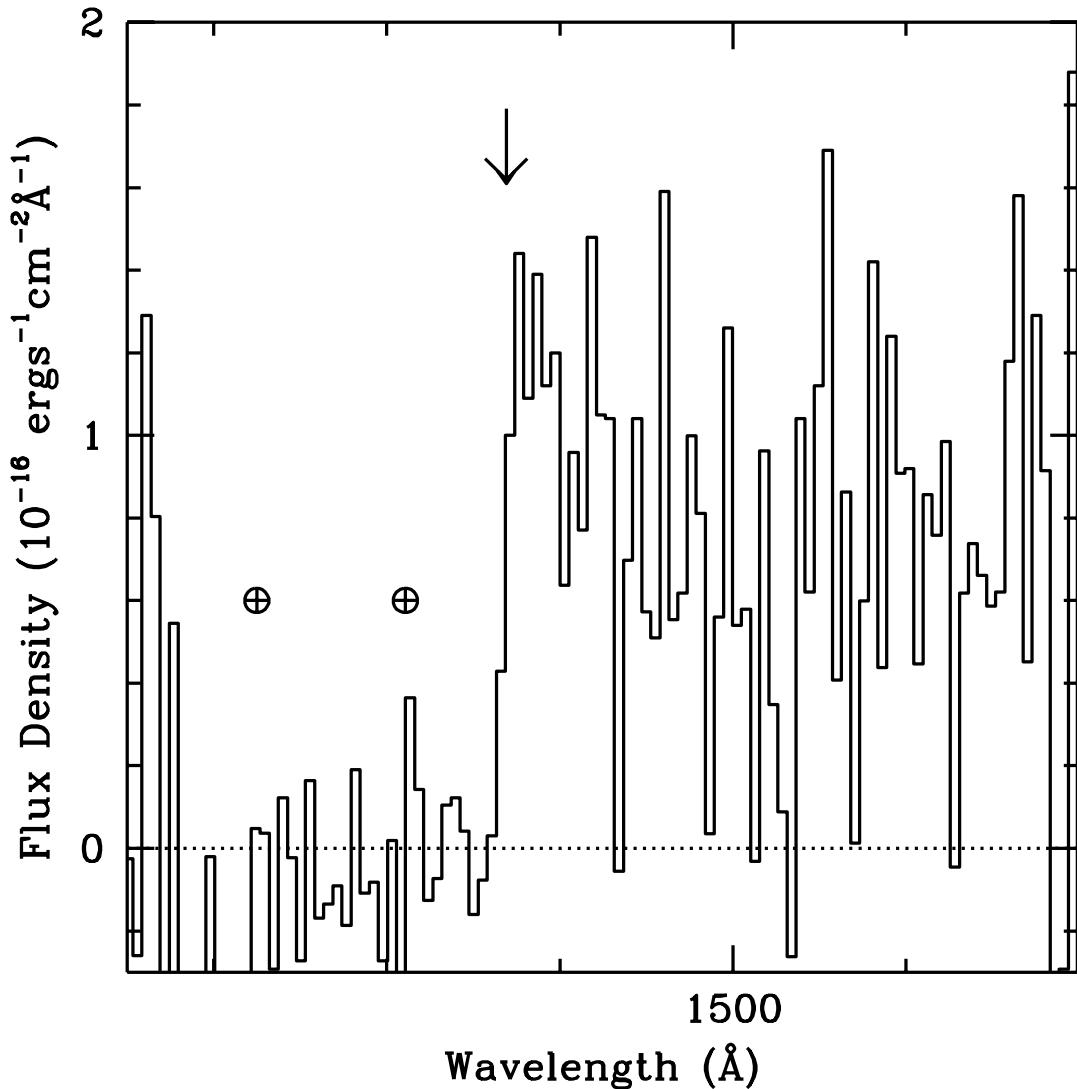


Fig. 3.— *HST/STIS* spectrum of quasar SDSSJ2346-0016. The G140L data are binned by nine pixels (~ 2.7 Å). The He II Ly α absorption edge is near the expected wavelength of 1370 Å. The Earth symbols mark the wavelengths of two strong airglow lines: Ly α and O I $\lambda 1304$.